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THE LOADING OF FILTER PLANTS¹

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The rapid growth of the inland cities of the United States and the extension of their sewerage systems have brought with them a serious public health problem in the marked increase that has taken place in the pollution of streams, used jointly as carriers of sewage and as sources of public water supplies. So rapidly has this condition developed along a number of the more important waterways that concern has been aroused among sanitary engineers as to how much further it can be safely allowed to continue unchecked, without threatening to break down the safeguards which modern water purification has erected between the sewage polluted source of water supply and the domestic consumer.

A good illustration of the rapidity with which the increasing pollution of our larger river systems has caused a progressive deterioration in the raw water supplies of certain important municipal filtration works is afforded by yearly average bacterial figures³ for the raw water taken from the Ohio River at the Cincinnati filtration plant extending over a period of twelve years from 1908 to 1919,

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³ Kindly furnished by Mr. Clarence Bahlman, Chief Bacteriologist at the Cincinnati Filtration Plant.

inclusive. Averaging these figures by three year periods, the results are as follows:

YEARS	BACTERIA PER CUBIC CENTIMETER (GELATIN, 20°C.)	B. COLI PER CUBIC CENTIMETER
1908-1910	8,400	
1911-1913	13,670	13.9
1914-1916	17,030	23.2
1917-1919	23,040	23.6

There are no cities of any considerable size located on the Ohio River or any of its tributaries within a distance of over 100 miles upstream from the Cincinnati water intake, so that the increase in degree of pollution of the river at this intake, as shown by the above figures, cannot be attributed to any influences local in their character, but are due solely to the effect of widespread increasing pollution of the upper Ohio River system. This example, while perhaps more striking than some others, is fairly representative of the changes that are occurring in a large number of important streams used as sources of water supplies, particularly in the more thickly settled portions of the Middle West.

A rational view of this problem, in the light of modern resources for dealing with it, recognizes first of all that public interest and economy demand the continued use of streams jointly for purposes of sewage disposal and water supplies. While the latter use must always take precedence over the former, it has become axiomatic that all water supplies taken from surface sources must be purified before delivery to the consumer. From a practical standpoint, therefore, the problem has become one of so regulating the pollution of streams that water purification plants taking their raw water supplies from them may be insured against becoming overloaded. The key to its most effective and economical solution lies, first, in determining, in measurable terms of stream pollution, what constitutes the maximum burden of pollution which may safely be imposed upon such plants and, second, in so utilizing the natural dilution and self-purification capacities of polluted streams that any threatened overburdening of these plants may be relieved at a minimum of expense. While the present paper deals largely with the first of these two questions, they are so intimately related to each other that any discussion of the one can hardly exclude some consideration of the other.

Until very recently, the belief was current that water purification plants of modern type, particularly with the introduction of chlorine disinfection, were capable of purifying satisfactorily a water of almost any degree of pollution, ordinarily at a cost within reasonable limits. More extended experience in operating such plants under various conditions, however, has demonstrated that there are more or less definite limits to the efficiency of water purification processes, this being especially true when the various economic factors entering into the problem are taken into account. Such experience, in fact, has shown more and more conclusively that these processes, under the economic and other limitations surrounding their operation, cannot with reasonable economy be made impervious to the passage of bacteria, nor can they ordinarily be so operated, under widely varying conditions of loading, as to produce effluents even closely approaching absolute constancy of bacterial content. Thus a purification plant may be likened to a series of barrier screens interposed in the path of polluting matter. The fineness of these "screens" may be increased by careful design of the plant and particularly by its efficient operation, but it cannot economically be made infinitely great, to the extent that the plant becomes an impassable barrier to polluting matter. This being true, a more or less definite relation should exist between the degree of pollution of a given raw water at various times and the bacterial character of effluent produced from it by a purification plant. From this relation, likewise, it should be possible to determine, at least empirically, the limits of safe bacterial loading for a given plant or type of plant, consistent with its production of an effluent of specified bacterial quality.

The first noteworthy action to this end was that of the International Joint Commission in adopting a bacterial standard of loading for filtration plants purifying Great Lakes waters as its guiding principle in regulating the pollution of the international boundary waters between Canada and the United States. This standard, in substance, provided that the average load upon any one of these plants should be such that the raw water delivered to it should not contain, as a yearly average, more than 500 *B. coli* per 100 cc., expressed in terms of the so-called *B. coli* index. In deriving this standard, it was assumed that effluents from purification plants treating Great Lakes waters should satisfy the United States Treasury Department requirements for interstate water supplies with

respect to *B. coli* content, which provide that water furnished for drinking purposes by interstate carriers shall not contain more than two *B. coli* per 100 cc., as determined by the *B. coli* index. While the International Joint Commission standard was admittedly a tentative one, derived from broad experience rather than experimental data, it was based upon extremely competent expert opinion and, as will be noted later, its general reasonableness has been confirmed rather strikingly by subsequent experiment.

About a year after the formulation of this standard, the United States Public Health Service, in connection with an extensive study of stream pollution in the Ohio River, made a study extending over about a year, of the operation of two modern and efficiently managed filtration plants taking their raw water supplies from this stream. The main object of this study was to determine by careful observation, under actual operating conditions from day to day, the maximum loading in bacterial terms which may be imposed with safety upon filtration plants purifying Ohio River water. It was believed that this loading, if found to be measurable, should furnish the best criterion available for fixing permissible limits of pollution for this river, after allowing for such factors as dilution and self-purification, which were made an object of extensive separate study. Without entering into the details of the filtration plant study, it is proposed to refer briefly herein to certain observations made and conclusions reached which have an important bearing on the present discussion.

Perhaps the most interesting and certainly the most important observation made in connection with this study was the close correlation found to exist between the bacterial content of the influent and that of the effluent in the purification process as a whole and in its various separate steps. At one of these plants, where the water is not chlorinated until after filtration, the correlation between raw water and filter effluent prior to chlorination was found to be particularly high, though in general it was also high enough as between raw water and final disinfected effluent to satisfy, by an ample margin, the usual statistical tests for correlation, such as the Pearson coefficient.

By grouping the data according to weekly average numbers of bacteria observed in the raw water and averaging coincident numbers in raw water and final effluent falling into each group, the correlation was shown as in table 1, the method here employed being the common "method of grouping" used by statisticians in studying

the nature of relations existing between two variables. It will be noted in connection with table 1 that an increase in bacterial content of the raw water is accompanied by an increase in the final effluent content, though the latter is not in direct proportion, as is indicated by the coincident decrease in the percentage of bacterial numbers remaining in the final effluent. In figure 1 is shown a plot of the percentage figures in terms of the gelatin 20° count. It is noted that these tend to approach a minimum value as the raw water count increases, indicating that the efficiency of purification tends with increased loading to approach a more or less well defined

TABLE 1
Relation between average numbers of bacteria in raw water and in final effluent, with varying amounts of former (effect of chlorination included)

	RAW WATER COUNT, RANGE	AVERAGE COUNT		PER CENT IN FINAL EFFLUENT
		Raw water	Final effluent	
Gelatin counts (20° C.) (Bacteria per cubic centimeter)	0 to 2,500	1,420	30	2.11
	2,501 to 5,000	3,680	36	0.98
	5,001 to 10,000	7,330	52	0.71
	Over 10,000	26,400	65	0.25
Agar counts (37°C.) (Bacteria per cubic centimeter)	0 to 1,000	574	7	1.22
	1,001 to 2,000	1,460	13	0.89
	2,001 to 4,000	2,790	20	0.72
	Over 4,000	6,800	30	.44
B. coli count (37°C.) (B. coli per 100 cc.)	0 to 1,000	898	2.3	0.256
	1,001 to 5,000	3,220	3.1	0.096
	5,001 to 20,000	8,270	4.5	0.054
	Over 20,000	30,900	6.0	.019

maximum. The curve shown in figure 1 is typical of similar curves defined by the 37 degree and B. coli counts in table 1.

By plotting the bacterial figures for raw water and effluent as given in table 1 on logarithmic ordinate and abscissae scales, the correlated values are found to plot along paths closely following straight lines, indicating that the relation between the two variables is that of a power function having the simple formula:

$$E = cR^n$$

in which (E) represents the bacterial content of the effluent, (R), that of the influent and (c) and (n), constants defining, roughly,

the average efficiency of purification and the relative constancy of effluent under different loadings, respectively. In general, the higher the value of (c), the lower will be the average efficiency of purification, while the higher the value of (n), the less uniform is the character of effluent obtained under different loadings. The above relation is very similar to that which was found by Wolman⁴ to govern the bacterial efficiency of a number of filtration plants in Maryland under different loadings, though his observation that the value of (c) approaches unity with sufficient closeness to be safely

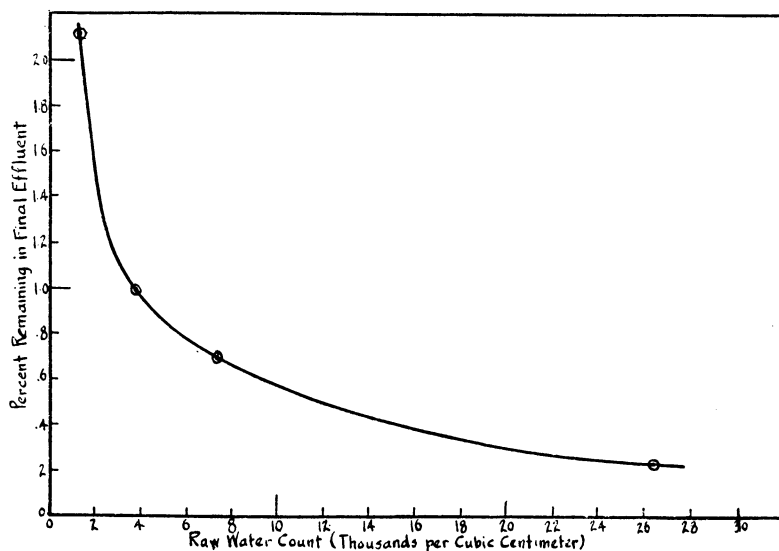


FIG. 1. RELATION BETWEEN NUMBERS OF BACTERIA IN RAW WATER AND THEIR PERCENTAGES REMAINING IN FINAL EFFLUENT.
(DATA FROM GELATIN COUNT IN TABLE 1)

disregarded was not confirmed in the case of the two Ohio River plants, as is indicated in table 2, giving values of the constants (c) and (n) derived from the plots in figure 2.

When the data obtained from the Ohio River study were analysed for each step of the purification process in a similar manner to that noted above, it was found that the relation between influent and effluent with respect to bacterial content was in each case governed by the same power function formula that has been described. In

⁴ See Journal, September, 1918, page 272.

TABLE 2

Values of constants (c) and (n) in formula: $E = cR^n$, defining bacterial efficiency of entire purification process, including chlorination (derived from plots in figure 2)

	(c)	(n)
Gelatin count.....	4.41	0.27
Agar count.....	0.23	0.55
B. coli.....	0.29	0.30

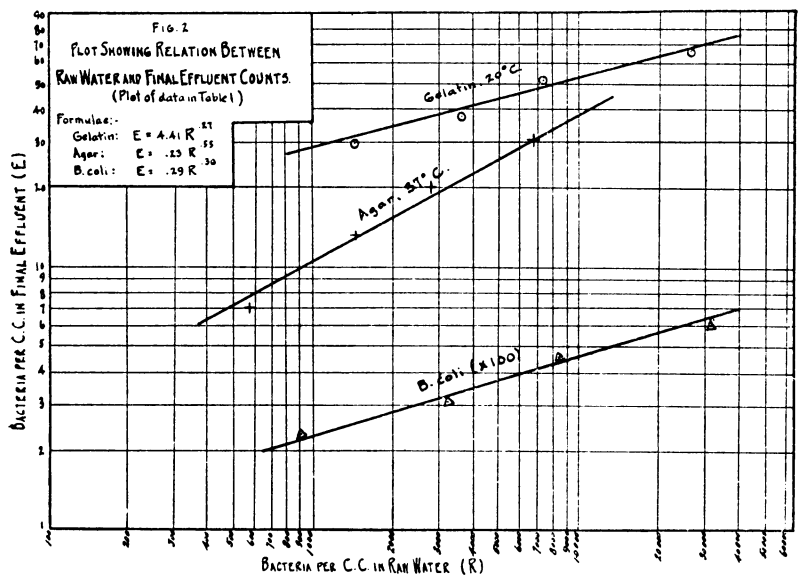


FIG. 2

TABLE 3

Values of constants (c) and (n) in formula: $E = cR^n$, for various steps of purification process (based on B. coli data in table 1)

	(c)	(n)
Plain sedimentation.....	7.10	0.66
Coagulation.....	0.31	0.65
Filtration.....	1.11	0.37
Chlorination.....	1.32	0.44

table 3 values of (c) and (n), based upon the *B. coli* relations, are given for each of the four steps of the purification process, the plots from which they were derived being omitted for brevity.

It will be noted that the loading constants above described have been derived wholly from bacterial correlations, taking no account of the effect of suspended matter, which is a powerful factor in the efficiency of all water purification processes. In the absence of further evidence, the point might well be taken that what has appeared as a function of bacterial numbers independently is in reality one of suspended matter, the bacterial correlations holding good in a given case because, in the purification of natural waters, quantitative changes in these two kinds of constituents follow each other more or less closely. If this were true, loading curves based upon

TABLE 4
Relative effects of variations in raw water turbidity and bacterial content upon percentages of raw water bacteria remaining in coagulated water

BACTERIA PER CUBIC CENTIMETER, RAW WATER	PERCENTAGES OF RAW WATER BACTERIA REMAINING IN COAGULATED WATER WITH RAW WATER TURBIDITIES OF			
	50-100 p.p.m.	100-250 p.p.m.	250-500 p.p.m.	500-1000 p.p.m.
A. 1,000-2,500.....	14.4	8.3		
B. 2,500-5,000.....	8.4	8.9	7.2	
C. 5,000-10,000.....			3.3	3.8

Note: Bacterial figures grouped primarily according to raw water turbidity; then results in each turbidity group re-grouped according to raw water bacterial content (groups A, B and C).

bacterial correlations alone might not necessarily apply to even the same raw water if its degree of bacterial pollution as related to its suspended matter content were to change materially. On the other hand, if the bacterial correlation were found to hold independently of the turbidity correlation, the fact that the latter also exists would not vitiate the applicability of the former.

In order to test this matter, observations similar to those previously cited were first divided into groups according to raw water turbidity, each group having a rather narrow turbidity range but presenting a wide variation in bacterial numbers. The data for each one of these groups were then sub-divided into a series of secondary groups according to raw water bacterial content. An example of the results obtained is given in table 4, based on a correlation of raw

and coagulated waters. It is noted in this table that, excepting in Group A, little variation in the percentages of residual bacteria occurs with increasing raw water turbidity, while a well marked decrease in these percentages takes place with increasing raw water bacterial content; indicating that, in general, the correlation between influent and effluent with respect to bacterial content is little affected by variations in turbidity, when these are unaccompanied by similar variations in bacterial numbers. From the above and other results obtained in similar analyses of the data, it was apparent that the influent-effluent correlation holds more or less independently with respect to bacterial content as far as the influence of visible turbidity is concerned, though, if it were possible to measure turbidity so finely divided and small in amounts as to be beyond the limits of visibility of present turbidimetric apparatus, it might be found that the numbers of bacteria in apparently clear filter effluents were closely related to their ultra-visible suspended matter content. However this may be, the evidence of the above observations points to the fundamental nature of the bacterial correlation between influent and effluent such as has been described.

It is next proposed to show how this correlation may be utilized in a practical way as a basis of predicting the probable loading conditions under which water purification plants, to which a given set of loading constants are applicable, are likely to become overburdened, as far as their producing effluents of specified bacterial quality is concerned.

If it be assumed that the values of (c) and (n) given in table 2 define a set of standard loading curves for purification plants taking their raw water supplies from the Ohio River, for example, the maximum loading values for these plants consistent with their production of effluents having any given bacterial content are readily ascertainable from the general formula that has been given. In table 5 a series of such values are given. By referring to the *B. coli* figures in this table it is noted that in order consistently to furnish effluents conforming to the Treasury Department standard, purification plants taking their raw water supplies from the Ohio River should have delivered to them water containing not more than an average of 650 *B. coli* per 100 cc., which corresponds quite closely with the International Joint Commission loading standard, previously cited, and thus affords an experimental confirmation of its general reasonableness. The close correspondence of these two

criteria when applied on a common basis is both interesting and significant, in view of their different methods of derivation and the wide differences existing between the two classes of waters for which they were derived.

A further example of the application of the constants given in table 2 is afforded by a rough test that was made of their general applicability as an index of the bacterial efficiency of a group of thirteen well known water purification plants of the rapid sand, gravity filter type, all located in the Mississippi valley where conditions are at least approximately comparable with those along the Ohio River. The test was made by use of published data for these plants given in a tabulation of figures for twenty-five plants of var-

TABLE 5

Maximum bacterial loadings consistent with production of effluents containing not more than specified numbers of bacteria, as defined by values of (c) and (n) in table 2

GELATIN, 20°C. (BACTERIA PER CUBIC CENTIMETER)		AGAR, 37°C. (BACTERIA PER CUBIC CENTIMETER)		B. COLI (PER 100 CC.)	
Final effluent	Raw water	Final effluent	Raw water	Final effluent	Raw water
30	1,200	10	930	2	650
40	3,400	20	3,300	3	2,500
50	7,600	30	6,800	4	6,600
70	26,000	50	17,000	5	14,000
100	95,000	70	31,000	7	42,000
		100	58,000	10	140,000

Note: Raw water figures in round numbers.

ious types by Hinman.⁵ One rapid sand plant listed by Hinman and located in the Mississippi basin (at Columbus, Ohio) was excluded from the test because of its being a combined softening and purification plant. Another (at Appleton, Wisconsin) was also excluded because its raw water supply was not regarded as being sufficiently typical of Mississippi basin waters to be entirely comparable with them. For two of the plants included, use was made of somewhat more complete data relative to 37° and B. coli results than were given in Hinman's table. Otherwise, the figures given in his table were used in their entirety.

⁵ See Journal, June, 1918, page 133.

The test was made by calculating from Hinman's raw water figures what the effluent count would be in each case if the efficiency of purification were assumed to be as defined by the values of (c) and (n) previously noted. The calculated values were then compared with the actual effluent figures as given in Hinman's table, with results as shown in table 6. With a few exceptions these results indicate a rather surprisingly close agreement between actual and calculated values, considering the variable factors of geographical location, raw water conditions and plant operation which might be expected to produce wide deviations in individual cases. To these factors of variation might also be added that of slight differences in laboratory methods, which experience has shown may produce wide deviations in bacterial results. The extremely close agreement between the average values shown at the bottom of the table give the results of the comparison greater significance, when all of the factors causing individual divergences in them are taken into account. While it is hardly probable that loading curves such as have been described could in their present state of development be in fairness applied as standards of efficiency for individual plants, the evidence cited above would most certainly indicate that they could be safely applied as criteria of safe loading with respect to a group of plants in a given drainage area as a guide for stream pollution regulation. Such evidence would suggest, moreover, that when further study of the question has advanced sufficiently to justify the more general adoption of loading standards for water purification plants, they may be found to be more uniform in character and wider in their field of application than might at present be supposed, in view of the known complexity of factors, frequently summed up as "local conditions," which affect the efficiency of different plants.

The formulation of any fixed standards of this kind, however, must finally be governed by whatever standard or set of standards may be adopted relative to the quality of purified water supplies intended for domestic consumption. This is evident from the figures given in table 5, which show that between comparatively narrow limits of variation in the required bacterial quality of filter plant effluents the permissible loading factor varies widely. The adoption of any definite policy relative to the limitation of stream pollution as far as it concerns the protection of water purification plants must likewise be governed by a similar standard.

While a discussion of water supply standards is hardly within the scope of the present paper, it is pertinent to emphasize that any standard which may be adopted relative to the quality of purified water supplies, as a criterion for stream pollution control, must, in

TABLE 6

Comparison of actual average numbers of bacteria in effluents of thirteen rapid sand filter plants in Mississippi basin with numbers calculated from actual raw water counts by formula: $E = cR^n$, using values of (c) and (n) as given in table 2

PLANT	GELATIN, 20°C.			AGAR, 37°C.			B. COLI		
	(Bacteria per cubic centimeter)			(Bacteria per cubic centimeter)			(B. coli per 100 cc.)		
	Raw water	Final effluent		Raw water	Final effluent		Raw water	Final effluent	
		Observed	Calculated		Observed	Calculated		Observed	Calculated
Decatur, Ill.....	7,200	49	49						
Quincy, Ill.....				2,080	11	16			
Evansville, Ind.....	1,250	50	30	5,000	45	44	78,000	7.0	8.4
Louisville, Ky.*.....	25,000	50	70	3,190	23	20	7,400	4.8	4.1
Minneapolis, Minn.....	2,250	24	35	775	7	8	1,500	0.2	2.8
St. Louis, Mo.....	81,000	170	95	12,000	16	41	3,100	1.7	3.2
Omaha, Neb.....	20,000	60	65	12,000	50	41			
New Orleans, La.....	2,900	38	38	200	14	4	35	0.5	0.8
Akron, O.....	1,830	34	34	246	11	5	130	0.9	0.6
Alliance, O.....	5,000	80	44	1,500	40	13	100	3.3	1.1
Cincinnati, O.†.....	13,900	48	58	1,920	19	15	2,140	4.6	2.8
Toledo, O.....	22,000	34	67				2,340	1.1	2.9
McKeesport, Pa.....	3,000	40	39	1,400	7	12			
Averages.....	15,440	56	52	3,660	22	19	10,540	2.7	3.0

* Agar and B. coli figures, average of daily results for one year.

† Agar figures, average of daily results for one year; B. coli figures, average for six years (1912-1917).

order to be applicable in a practical way, be expressed in terms similar to those by which both stream pollution and filter plant efficiency may be directly measured. In other words, the three variables, filter plant loading, filter plant efficiency and quality of effluent, must be expressed in common terms in order to be mutually

convertible. While so-called engineering criteria, such as the sanitary survey, may ultimately become sufficiently developed and correlated to permit the formulation of standards in these matters expressed in more fundamental terms, virtually the only criterion available at the present time which fulfills the above conditions is the bacteriological determination. With all of their admitted faults, bacterial criteria have the very practical advantage of being in common use. Efforts to improve them will, for the present at least, probably be far more fruitful of practical results than attempts to develop standards of a more fundamental character.

In addition to a definition of standards for filter plant effluents, further knowledge of the problem discussed in this paper is needed along the following lines:

1. As to the influence of seasonal and climatic factors, type of raw water, relative age of its pollution and operation conditions upon the efficiency of water purification plants and upon their limits of safe loading.
2. As to the role of chlorination in relation to filtration processes in determining their limiting safe loading.
3. As to the economic limits of water purification as related to stream cleaning measures.

It was noted in the study of Ohio River plants that seasonal factors, particularly temperature, have an important relation to the efficiency of filtration processes employing coagulation. It has also been commonly observed that seasonal changes in the character of suspended matter carried by many natural streams materially affect the efficiency of purification plants at certain times. As to the possible influences exerted by variations in type of raw water and relative age of its pollution upon the character of effluents obtainable under given conditions of loading as measured in bacterial terms, virtually no data are at present available. Knowledge of these matters will be of particular importance in determining what weight should be given to variations in raw water composition, as related to its average character, in fixing standards of loading for plants in a given locality.

There is of course no question of the great importance of chlorination as an aid to water purification, nor can there be any doubt that its general introduction has actually relieved from threatened or existing overburden many plants forced to treat highly polluted waters. A question remains, however, as to whether, in fixing per-

missible limits for the pollution of raw water supplies chlorination should be considered as an integral part of the purification plants drawing upon these supplies or should be held in reserve as a factor of safety. A fairly general agreement on this question is essential to the adoption of loading standards having wide acceptance.

Finally, there remains the question as to what are the economic limits of water purification as related to those measures of stream cleaning which involve extensive sewage treatment programs. Is it, for example, economically justifiable to consider seriously the development of water purification plants beyond their present degree of elaboration in order to increase their limits of safe loading and thereby minimize correspondingly the expenditure of funds for systematic stream cleaning? There are theoretically a number of possible ways of accomplishing this, among which might be noted the construction of large auxiliary storage reservoirs and the use of secondary treatment processes. But these measures would involve greatly added costs of water purification, against which are to be balanced the growing possibilities for securing at a nominal expense a sufficient degree of relief for many overburdened streams through partial treatment of the sewage and other harmful wastes discharged into them. On the latter side of the balance sheet are to be added the benefits to be realized from stream cleaning in addition to the relief of overburdened water purification plants. In some cases these may prove to be determining factors in the equation.

In general, however, the most economical solution of problems of this kind must finally depend upon local conditions governing the use of a particular stream for water supply and sewage disposal purposes, such as, for example, the distribution of waste-contributing population on its drainage area and its natural dilution and self-purification capacities. A recapitulation of the present cost factors entering into water purification and sewage treatment, together with data regarding the laws and principles underlying stream pollution and purification phenomena, such as are being gathered by the United States Public Health Service in connection with its stream pollution studies, will aid materially in affording a definite basis for the solution of problems of this kind.

In conclusion, it may be reiterated that the excessive loading of water purification plants in the more populous sections of the country is rapidly assuming the proportions of a widespread and serious problem, in spite of the remarkable progress that has been

made in lowering the typhoid fever rate in a large number of our cities. The discovery and general use of chlorine disinfection as an aid to filtration processes has in many cases turned the scale from imminent danger to temporary safety, but it cannot be too strongly emphasized that in view of the present trend in the increasing pollution of inland streams the safety thus gained is but temporary. Unless, as appears unlikely, advances of a revolutionary character should occur in the art of water purification, systematic measures for relieving over-pollution of streams used as sources of public water supplies will be necessary in a number of large river systems within a comparatively short time. If these measures are to be scientifically applied, with due regard to the enormous economic interests involved, the fullest possible use must be made of both the natural purification forces at work in polluted streams and such artificial methods as modern water purification provides. The work of the Public Health Service, which has been referred to rather extensively in this paper, has been consistently aimed toward an evaluation of these measures in fundamental terms. Further studies of loading factors for water purification processes, however, are needed, somewhat broader in scope and more intensive in their experimental features than those which have thus far been made of the question. The present paper has been written with the hope that it will stimulate discussion and coördinated effort toward this end.